ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #36889

Physically Contextualized Machining Instructions through Augmented Reality

Emma Rose Higgason

Ms. Higgason is a sophomore at MIT majoring in mechanical engineering with a concentration in product development. Her primary interests include engineering education, augmented reality, and hands-on machining work.

Gabrielle Enns

Joseph Wight

Emily Welsh (Educational Technologist)

Ms. Welsh works as an educational technologist in the LEAP Group at MIT. Her work includes the development and running of MOOCs, the development of digital education tools, and researching how digital tools impact learning. Her background is in mechanical engineering with a focus on manufacturing. Prior to joining MIT, she worked at an original equipment manufacturer.

A. John Hart

John Hart is Professor of Mechanical Engineering, Director of the Laboratory for Manufacturing and Productivity, and Director of the Center for Additive and Digital Advanced Production Technologies at MIT. John's research and teaching efforts focus on the science and technology of manufacturing. He is a co-founder of Desktop Metal and VulcanForms, and is a Board Member of Carpenter Technology Corporation.

John Liu

Dr. John Liu is the principal investigator of the MIT Learning Engineering and Practice (LEAP) Group, which applies design and systems principles to solving challenges in learning and develops learning experiences to better meet the increasing demand for STEM skills in tomorrow's workforce. He is a Lecturer in MIT's Mechanical Engineering department and Scientist of the MITx Digital Learning Laboratory. Dr. Liu's work includes engineering education, mixed reality and haptic experiences, workforce solutions to address the nation-wide manufacturing skills gap, open-ended assessments for scalable education settings, and instructional design theory for massively open online courses.

Physically Contextualized Machining Instructions through Augmented Reality

Abstract

Hands-on fabrication skills require complementary capacity for spatial thinking, but teaching often relies on 2D drawings to render inherently three-dimensional concepts. Computer-aided Design (CAD) software provides robust engineering visualization, but 3D models are displayed on a 2D screen and separate from the learner's physical context. Augmented Reality (AR) is another 3D technology that has the potential to facilitate embodied learning and an introductory student's transfer of concepts to tasks, because of its ability to integrate three-dimensional information into the physical context of authentic tasks.

We present the design, development, and initial course implementation of AR instructions to fabricate a metal flashlight using common fabrication tools and equipment in the machine shop. The app gives written instructions and engineering drawings, accompanied by an AR visualization of how the workpiece changes step-by-step and how all of the parts are eventually assembled. This app has now been released into an undergraduate-level introductory fabrication course ("Mechanical Engineering Tools") at the Massachusetts Institute of Technology (MIT). We developed pre- and post-assessments to measure cognitive and affective outcomes and compare outcomes between a pilot AR-based cohort (N=6) to the traditional cohort (N=20). A psychomotor assessment was also carried out for a subset of the cohorts. This work suggests AR-enhanced instruction may promote learning transfer in hands-on skills training.

1. Introduction

In fields ranging from design, construction, architecture, and engineering, there is an increasing interest in the creation of three-dimensional (3D) models and the establishment of "interrelationships between modeling components" [1]. In engineering education, the ability to think in such spatial contexts is often a barrier to entry [2], [3]. 3D technologies, such as Computer Assisted Design (CAD), are potential tools to overcome such barriers. But even when these 3D technologies are implemented, the challenge arises when students are expected to apply their learned content in authentic practice. Tools like Augmented Reality (AR) can support the transfer of information to "real world" situations, making it an effective, modern teaching method [4]. AR presents 3D lessons that enable students to digest the information in a novel and interactive way, meaning AR can serve as a bridge between knowledge and context. The implementation of AR can not only contribute to students' spatial thinking abilities, but it can also allow them to learn more efficiently in an increasingly technologically advanced world [5].

Embodied learning is another area of education that stands to be improved with AR. Embodied learning refers to the non-mental parts of learning, such as physical body involvement [6]. Students are more likely to connect old and new knowledge when learning in highly embodied lessons, making it an effective learning method [7]. AR, and other mixed reality environments, promote such embodied learning by getting the student physically involved with their learning experience [7].

Beyond the knowledge that is acquired in the classroom, when students enter the workforce, therein also lies challenges associated with "institutional knowledge" or "rules of thumb": knowledge passed down through generations of workers [8]. Much of this institutional knowledge is undocumented [9]. AR has been proven to play a promising role in the efficient archiving and dissemination of knowledge in manufacturing firms and is a potential solution to issues created by inconsistencies in the availability and communication of institutional knowledge [10]. AR can digitize information capture processes that can then be confirmed and passed down to the new generation of industrial workers [9]. When information and knowledge are communicated effectively, this can lead to "efficiency, quality, minimizing waste, and creating a common understanding between individuals" [8].

This paper presents the development of an app with the goal of using AR to promote successful knowledge transfer through the construction of an aluminum flashlight.

2. Pedagogy and Background

The AR app was developed based on the pedagogy of an introductory course, "Mechanical Engineering Tools," at MIT. The course consists of twelve hours of work time split over three days. The course was created to give engineering students a baseline understanding of how to use the basic machine shop tools related to mechanical engineering, and to emphasize related safety considerations. Students receive training on how to safely conduct themselves in a machine shop, as well as instruction on a 3-axis vertical milling machine, horizontal lathe, vertical and horizontal bandsaws, belt sander, hand file, deburring tool, and sandpaper. For the vertical mill, students learn how to edge find, drill, tap, bore with an endmill, and face mill using both climb cuts and conventional cuts. With the lathe, students learn to face, turn, drill, tap, knurl, part, and debur their material.

Students learn these hands-on skills by fabricating a two-part metal flashlight (Figure 1). The circular body of the flashlight contains the battery and is designed to be made on the lathe. The rectangular head contains the light bulb and is designed to be made on the mill. Both parts were designed to require a range of work holding positions, setups, tool options, and tolerancing practices. The course stresses the importance of dimensions and tolerances by regularly encouraging students to check their work and compare their measurements to dimensioned drawings. The intended outcome of this course is to give students the knowledge of what each machining process can do and the confidence to work in a machine shop environment. This course fulfills a hands-on training prerequisite for the introductory (full-semester) design and manufacturing course (typically taken by second-year undergraduates); this and several upper-level core mechanical engineering courses require the use of the machine shop for project-based learning.

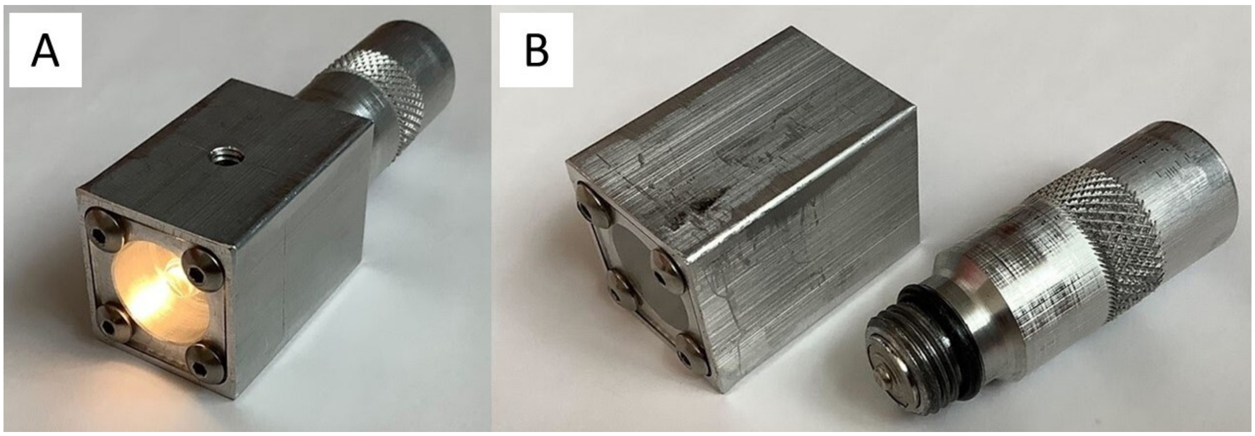


Figure 1: A) the assembled flashlight is composed of B) a rectangular head machined on the mill and a cylindrical body machined on the lathe.

3. Design and Development

The app is designed to assist students in learning how to machine an aluminum flashlight. The app offers written text instructions, 3D CAD models, a view of part dimensions, and a cross-section view. Users can visualize the workpiece before and after the material is removed in each process step. Instructions specific to each step are available alongside the visual 3D portrayal of the material. The AR app contains illustrated steps of the milling and turning stages of the fabrication, and an assembly stage containing an animation of the flashlight being assembled from its finished parts. We used Vuforia Studio created by PTC Inc. Vuforia Studio enables the user to create an interactive AR interface with a combination of drag and drop widgets and coding in JavaScript. We used SolidWorks to create CAD models of the flashlight for the students to interact with. Creo Illustrate was used to create the final assembly view with animations.

Analyzing the existing course pedagogy led to the following app design decisions.

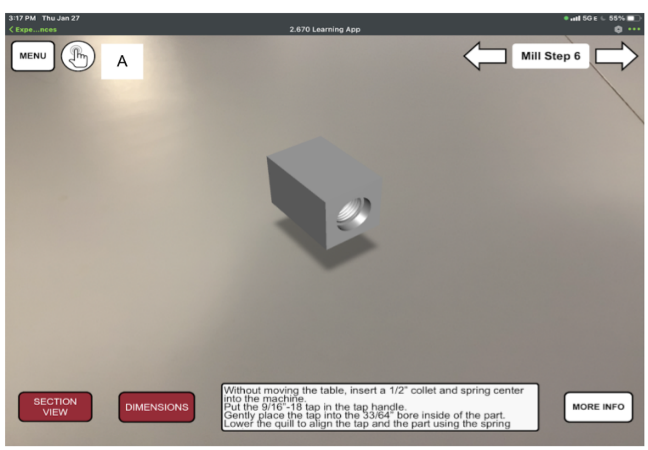
1. To ground the experience of creating a flashlight in physical 3D space, we opted to use AR rather than other 2D paper alternatives.
2. The course "Mechanical Engineering Tools" typically uses a printed instruction manual, so the focus was to develop a version of the instructions enhanced by AR and presented on a tablet device. The physical packet included dimensions, step-by-step instructions,

and cross-section drawings, so we incorporated these elements into the app design.

The app flow proceeds between the home screen, milling steps, lathe steps, and the assembly view (Figure 2). At any point during app use, the user can switch to a different area of the app using the menu button. The home screen has several functionalities. The user can view the step-by-step AR models or access the written PDF containing the instructions in traditional form. The step-by-step button will bring the user immediately to the first milling step. From there, they can either go to the lathe or assembly steps using the menu button, or proceed forward with the milling steps. The original written instructions were included in PDF form accessed by the app because the PDF contained elements like engineering drawings that were not incorporated into the main app experience. There was also supplemental instructional material in the packet, such as the difference between climb and conventional milling, which was not included in the app.

Figure 2: Navigation through the flow of app usage.

The app overlays a digital model onto a flat surface of the user's physical context (Figure 3A), exemplifying the model view with the dimension and section views toggled off. Upon pressing the dimension button (Figure 3B), the relevant dimensions for a given step will be shown on the model. We avoid including miscellaneous dimensions in the initial view to keep the AR experience as clean as possible. The section view (Figure 3C) is especially helpful for the milling steps because the mill is used to create the flashlight pocket. When students are milling in real life, it is difficult to know what is happening inside the pocket, but with the AR experience, it is possible to split the model in half to see the internal features. This increases students' ability to understand the internal geometry, which is less intuitive based on the paper instructions alone.



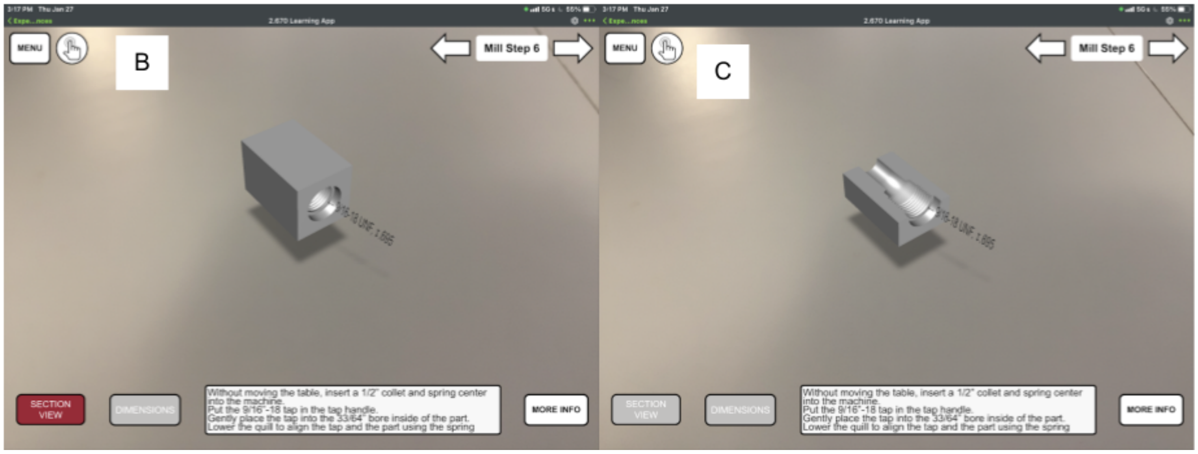


Figure 3: The app gives step-by-step instructions, A) overlays a digital model onto a flat surface of the user's physical context, B) displays dimensions, and C) a cross-section of the workpiece in the current state of the step.

While most of the buttons on the app's user interface are labeled with their function, users can toggle the "more info" button (Figure 4E) which will bring up a screenshot of the PDF of instructions. The button that says "Mill Step 6" (Figure 4G), will cause a pop up enabling students to travel to any milling step. Pressing the icon with a pointing hand on it (Figure 4H) will cause a pop-up showing the different gestures one can use with the iPad to interact with the AR environment. Using a two-finger pinch, the model can be adjusted to any size or orientation that best helps the student understand the task at hand.

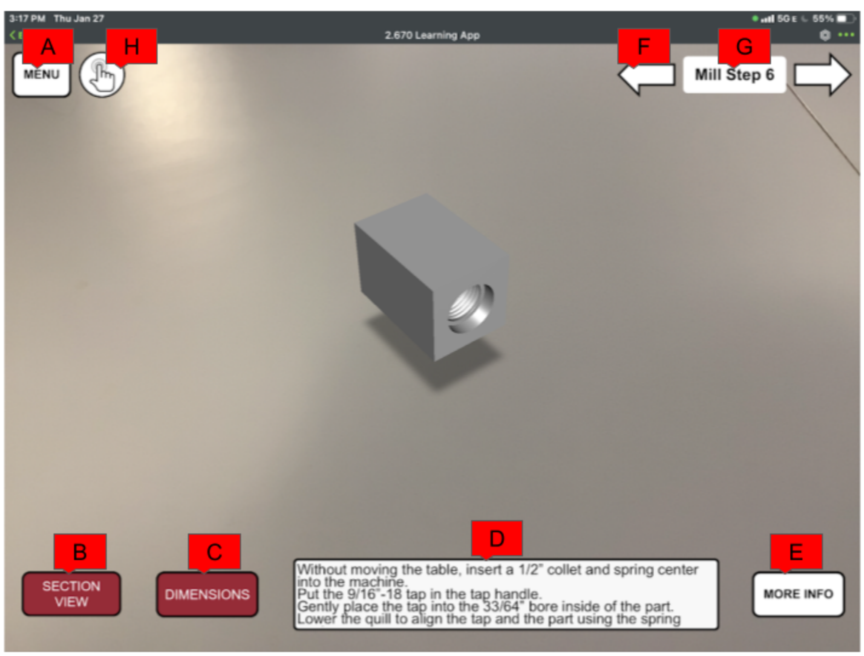


Figure 4: User interface of the app during the initial step preview: A) menu, B) section view, C) dimension view, D) written instructions, E) more info, F) arrows, G) step number, H) touch navigations.

After the flashlight head housing is made using the mill, the handle is made using the lathe (Figure 5). The screen is set up similarly to the milling steps, with the same buttons being available to students so they can view dimensions and section views (which become more relevant when drilling the battery pocket).

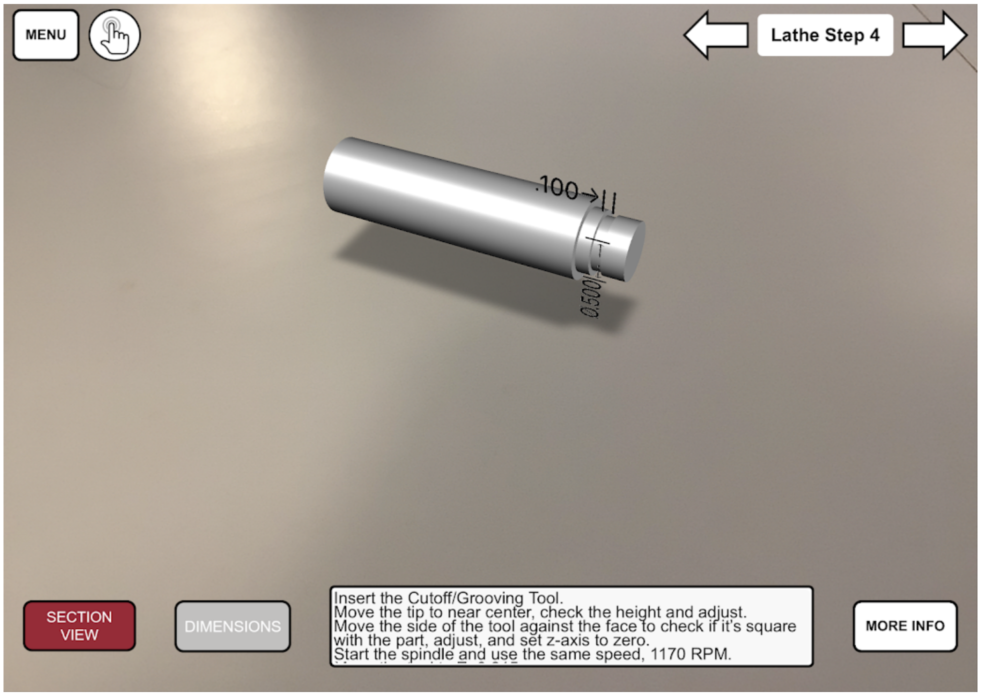


Figure 5: A representative screenshot of a lathe step.

The final step in creating the flashlight is assembly. The initial view of the assembly shows all of the fabricated parts laid out (Figure 6A). A sequence of several animated steps matches the parts together until the flashlight is fully assembled (Figure 6B).

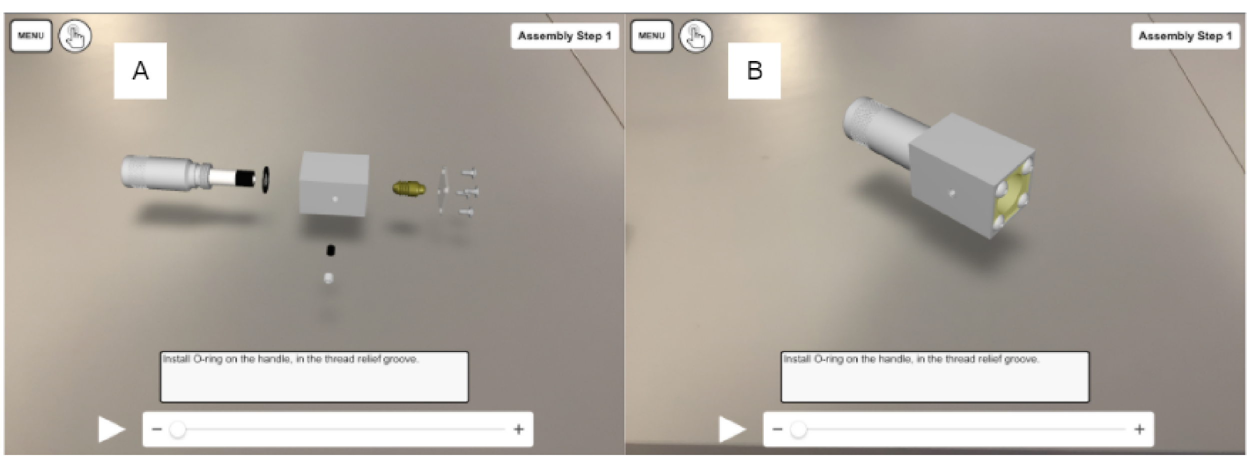


Figure 6: A) initial assembly view and B) final assembly view.

4. Methodology

The experimental group consisted of 27 students enrolled in the course Mechanical Engineering Tools and were primarily first-year students intending to pursue a major in mechanical engineering. Students were broken into two groups. Group A (N=6) received their instructions through a combination of the augmented reality app and a machine shop instructor. Group B (N=21) served as the control group and received instruction by the traditional paper handout, alongside a machine shop instructor. Each group completed a pre-assessment before receiving any instruction in the course and a post-assessment after the course was completed.

The first section of the pre-assessment activity measured affective outcomes and consisted of twenty-one questions on a 7-point Likert scale (1- “not at all true of me” to 7 – “very true of me”) adapted from the *Motivated Strategies for Learning Questionnaire* (MSLQ) [11]. Twelve questions were written to check for three types of self-efficacy: an individual's belief in one’s capacity to learn the content (3 questions), apply the necessary skills to equipment (5 questions), and to perform well in the class (4 questions). Five questions checked the students' motivation to re-engage with the content and four questions measured their fear of making mistakes. Each theme was covered by multiple questions to measure the average over multiple questions to normalize for variation in question phrasing and learner response. The second section measured cognitive outcomes where students were asked a series of twenty questions on technical aspects of machining. These questions were adapted from the National Institute for Metalworking Skills (NIMS) Machining Level 1 Preparation Guides for Milling and Turning [12], [13]. The content questions covered the following categories: component identification, operations, work holding devices and basic setup, safety, process improvement and troubleshooting, tapping, fits and allowance, and measurement.

The post-assessment activity repeated the twenty-one Likert scale questions and the twenty technical questions from the pre-assessment. The post-activity asked if the students had used the paper or AR instructions. The third section of the post-assessment consisted of three 7-point Likert scale questions:

1. *I liked learning using the format I received.*
2. *I learned the necessary material using the format I received.*
3. *I would prefer to learn machining using the format I was given as opposed to the other format.*

Two additional open response questions asked how the format they used affected their learning and if they had any additional comments. The pre-assessment and post-assessment activities are included in the Appendix.

We compared the affective outcomes in pre- and post-assessments for both the AR and traditional groups to determine how completing the course changed the students' self-efficacy, motivation, and fear. The affective pre- and post-assessment data was analyzed by categorizing the data by question type. The average and standard deviation were taken for the grouped responses for each question type. A paired t-test was carried out to find the confidence interval between the pre- and post-assessment values. The hypothesized mean difference (HMD) was then calculated based on the t-test, means, and standard deviation. The result of this analysis is given in Table 1.

We compared the cognitive pre- and post-assessments for both the AR and traditional groups to determine how completing the course changed the students' cognitive understanding of the course content. The cognitive assessment was scored by staff resulting in the total quiz score out of a possible twenty points. Blank answers were scored as incorrect answers. To test changes in specific areas of knowledge, the cognitive assessment was categorized by question type. The average, standard deviation, paired t-test, and hypothesized mean difference were found for both the total score and each category. The result of this analysis is given in Table 2.

The data was then analyzed to compare the effectiveness of AR against traditional teaching in influencing self-efficacy, motivation, and fear. The change in affective assessment scores between the pre- and post-assessments for the two groups was compared as well as the three Likert scale questions on learning method. A two-sample unequal variance t-test was performed to determine if the difference between the changes in affective outcomes of the two groups had statistical significance. From this t-test, the HMD was calculated as the difference between the AR and traditional cohort. The HMD is positive if the AR cohort had a higher change in score than the traditional cohort. The results of the analysis are given in Table 3.

Similarly, the change in cognitive assessment score was compared between the two groups using a two-sample unequal variance t-test. The results of this analysis are given in Table 4.

5. Results

For both the traditional and AR cohorts, we determined that the course results in a statistically significant increase in self-efficacy and motivation to re-engage (alpha=0.5). We also see a decrease in the fear of making mistakes in both cohorts. This implies that both cohorts of students had higher self efficacy, were interested in machining more, and had a lower fear of failure than when they started the course. Student open response feedback supports this. For example, one student commented “I learned so much! I really enjoyed using the Mill and Lathe. Learning while building was so much fun.”

AR Cohort (N=6)							
	Pre		Post		Paired t-test P-Value	Confidence Value	HMD
	Average	Sample σ	Average	Sample σ			
Self-efficacy - Learning: (Questions 2, 10, 11)	5.78	0.94	6.67	0.49	0.00	99.99%	0.89
Self-efficacy - Application: (Questions 1, 4, 6, 7, 13)	4.63	2.06	6.53	0.57	0.00	100.00%	1.90
Self-efficacy - Performance: (Questions 9, 15, 19, 20)	5.83	1.17	6.46	0.59	0.00	99.56%	0.62
Motivation to Re-engage: (Questions 5, 12, 14, 17, 21)	5.80	1.27	6.17	1.26	0.04	96.12%	0.34
Fear of Making Mistakes: (Questions 3, 8, 16, 18)	3.13	1.36	2.04	1.12	0.00	99.79%	-1.08
Traditional Cohort (N=20)							
	Pre		Post		Paired t-test P-Value	Confidence Value	HMD
	Average	Sample σ	Average	Sample σ			
Self-efficacy - Learning: (Questions 2, 10, 11)	5.38	1.40	6.13	0.89	0.00	100.00%	0.75
Self-efficacy - Application: (Questions 1, 4, 6, 7, 13)	4.08	2.10	5.97	1.02	0.00	100.00%	1.89
Self-efficacy - Performance: (Questions 9, 15, 19, 20)	5.59	1.06	6.40	0.76	0.00	100.00%	0.81
Motivation to Re-engage: (Questions 5, 12, 14, 17, 21)	5.61	1.36	5.98	1.35	0.01	99.16%	0.36
Fear of Making Mistakes: (Questions 3, 8, 16, 18)	3.60	1.67	3.10	1.60	0.02	97.79%	-0.52

Table 1. *Pre- and Post-Assessment Affective Data for AR and Traditional Cohorts.*

The overall quiz scores improved for each group with a 98.26% confidence for the AR cohort and a 99.97% confidence for the traditional cohort. Due to the small sample size of the AR cohort, increases within each question type have lower confidence. For the traditional cohort, we can see a statistically significant score increase in knowledge of components, work holding devices and setup, and safety. The HMD score increases for each category are relatively small however. This modest increase in conceptual understanding could owe to the fact that the course is focused on practice and not theory. A student in the traditional cohort commented "I enjoyed being able to gain hands-on experience with the machines. I don't feel as though I learned much jargon or theory, though."

AR Cohort (N=6)							
	Pre		**Post**		**Paired t-test P-Value**	**Confidence Value**	**HMD**
	Average	Sample σ	Average	Sample σ			
Total Quiz Score (Out of 20)	11.83	2.99	15.17	2.93	0.02	98.26%	3.30
Component Identification (Questions 1,2,3,6,7,8)	0.83	0.38	0.94	0.23	0.10	89.68%	0.09
Machine Operations (Questions 9,10,11,18,20)	0.53	0.51	0.70	0.47	0.13	86.60%	0.13
Work Holding Devices and Basic Setup: (Questions 4, 5,19)	0.56	0.51	0.72	0.46	0.19	81.28%	0.11
Tapping Fits and Allowance: (Questions 14, 17)	0.33	0.49	0.58	0.51	0.08	91.81%	0.23
Process Improvement and Troubleshooting: Question 12	0.33	0.52	1.00	0.00	0.03	97.50%	0.66
Safety: Question 13	0.33	0.52	0.33	0.52	1.00	0.00%	-0.30
Measurement: (Questions 15,16)	0.58	0.51	0.67	0.49	0.34	66.12%	-0.02
Traditional Cohort (N=20)							
	Pre		**Post**		**Paired t-test P-Value**	**Confidence Value**	**HMD**
	Average	Sample σ	Average	Sample σ			
Total Quiz Score (Out of 20)	11.25	2.38	13.95	2.37	0.00	99.94%	2.70
Component Identification (Questions 1,2,3,6,7,8)	0.77	0.42	0.92	0.28	0.00	99.88%	0.15
Machine Operations	0.54	0.50	0.62	0.49	0.17	82.87%	0.05

(Questions 9,10,11,18,20)							
Work Holding Devices and Basic Setup: (Questions 4, 5,19)	0.37	0.49	0.73	0.45	0.00	100.00%	0.37
Tapping Fits and Allowance: (Questions 14, 17)	0.33	0.47	0.45	0.50	0.20	79.95%	0.09
Process Improvement and Troubleshooting: Question 12	0.70	0.47	0.80	0.41	0.33	67.01%	0.05
Safety: Question 13	0.00	0.00	0.15	0.37	0.08	91.72%	0.14
Measurement: (Questions 15,16)	0.75	0.44	0.65	0.48	0.32	67.65%	-0.15

Table 2. *Pre- and Post-Assessment Cognitive Data for AR and Traditional Cohorts.*

The changes in affective outcomes are compared between both cohorts in Table 3. At an alpha of .05, there are no statistically significant differences in the average affective changes between the AR and the traditional cohort. To gain insights into the perceived differences by students, we can reference the open response questions. In the open response questions, students commented, for instance, "With the AR it was interesting to see how the part changed as I moved along, and it was cool to be able to zoom in to see what the part should look like at each step." The sample size for the learning method questions was low because there was only one question per type and we cannot draw conclusions with confidence from the results.

	AR Post-Pre (N=6)		**Traditional Post-Pre (N=20)**		**2 sample unequal variance t-test P-Value**	**Confidence Value**	**HMD (AR-Traditional)**
	Average	Sample σ	Average	Sample σ			
Self-efficacy - Learning: (Questions 2, 10, 11)	0.89	0.76	0.75	1.22	0.56	43.78%	0.00
Self-efficacy - Application: (Questions 1, 4, 6, 7, 13)	1.90	1.94	1.89	1.93	0.98	1.97%	-0.38
Self-efficacy - Performance: (Questions 9, 15, 19, 20)	0.63	0.97	0.81	0.90	0.40	59.58%	-0.28
Motivation to Re-engage: (Questions 5, 12, 14, 17,	0.37	0.93	0.37	1.38	0.99	1.21%	-0.22

21)							
Fear of Making Mistakes: (Questions 3, 8, 16, 18)	-1.08	1.53	-0.50	1.92	0.13	86.98%	-0.63
Section 3: Learning Method Feedback							
I liked learning using the format I received.	4.67	1.03	5.55	1.36	0.12	88.23%	-0.94
I learned the necessary material using the format I received.	5.83	1.17	5.65	1.27	0.75	25.11%	-0.23
I would prefer to learn machining using the format I was given as opposed to the other format.	3.50	2.07	5.05	1.76	0.14	86.10%	-1.68

Table 3. *Change in Pre- and Post-Assessment Affective Assessment Scores for AR and Traditional Cohorts.*

The cognitive post-assessment data was also analyzed to compare the effectiveness of AR against traditional teaching (Table 4). Again, there are no statistically significant differences between the two cohorts in cognitive outcomes.

	AR Post-Pre (N=6)		**Traditional Post-Pre (N=20)**		**2 sample unequal variance t-test P-Value**	**Confidence Value**	**HMD (AR-Traditional)**
	Average	Sample σ	Average	Sample σ			
Total Change in Quiz Score	3.33	2.34	2.70	2.94	0.60	40.36%	-0.05
Component Identification (Questions 1,2,3,6,7,8)	0.11	0.40	0.15	0.50	0.63	37.00%	-0.09
Machine Operations (Questions 9,10,11,18,20)	0.17	0.59	0.08	0.58	0.48	51.65%	0.03
Work Holding Devices and Basic Setup: (Questions 4, 5,19)	0.17	0.51	0.37	0.58	0.17	82.93%	-0.22
Tapping Fits and Allowance:	0.25	0.45	0.13	0.61	0.45	55.20%	0.05

(Questions 14, 17)							
Process Improvement and Troubleshooting: Question 12	0.67	0.52	0.10	0.45	0.04	95.63%	0.56
Safety: Question 13	0.00	0.63	0.15	0.37	0.60	40.04%	-0.31
Measurement: (Questions 15,16)	0.08	0.29	-0.10	0.63	0.17	83.35%	0.16

Table 4. *Change in Pre- and Post-Assessment Cognitive Assessment Scores for AR and Traditional Cohorts.*

The open response feedback from students was largely positive, with students expressing enjoyment of the course. The AR cohort gave valuable feedback on how to improve the app for future course iterations for example: "The AR functions were sometimes unintuitive and the pieces were hard to rotate." Traditional students commented on the value of having the packet to review between course sessions "Having the packet of material on hand was useful for reference outside of the scheduled sessions to get an understanding of the tasks beforehand as well as for reference during the sessions to ensure that all steps were being taken in the correct order and manner." Two traditional students also commented that they would not have been comfortable bringing their iPad into the machine shop as it may have gotten dirty.

6. Conclusion and Future Work

We developed and introduced an AR app that gives instruction on the use of machine shop tools through an introductory (12-hour) undergraduate tutorial course. This app was intended to use augmented reality (AR) to enable contextualized learning and promote successful knowledge transfer. The app overlaid onto a user's physical space a digital representation of flashlight fabrication including instructional text, dimensions, and section views. Future development work of the app experience will be focused on developing animations of tools machining the workpiece, clearer text instructions and dimensions, the addition of technical drawings displayed next to the part for visual reference, and expanded instructional text, with the goal of improving the student and instructor machining experience and reducing resistance to AR. The machine shop will provide tablets to alleviate student concerns about damage to their personal equipment The app is also currently optimized for the tablet experience, and having a companion smartphone experience could help with accessibility to those who do not have access to tablets. Another barrier to implementation is that it is unreasonable to assume the instructor is able to serve as the primary source of troubleshooting and demonstrating the app. To circumvent this issue, we aim to reduce bugs and improve ease of user experience.

Our pre- and post-assessments show that separate cohorts using either the app or printed instructions display a statistically significant increase in self-efficacy and motivation to re-engage with the content, as well as a decrease in the fear of making mistakes. This implies that by the end of the course, both cohorts of students had stronger beliefs in their ability to learn, apply, and perform machining skills, were interested in machining more, and had a lower fear of failure than when they started the course. In the past, educational AR experiences have led to frustrating or inferior learning due to issues such as poor usability or cognitive overload [14]. However, we did not see statistically significant differences in the increases of cognitive or affective outcomes between the two cohorts. Because this course teaches fabrication, differences in learning outcomes between the two cohorts may be found in hands-on skills or visualizing 3D operations instead of conceptual understanding. By providing students with visual representations of the process integrated into their physical context, AR could enable a smoother and more accurate transfer of their knowledge to the authentic task. In future work, these advantages may eventually be measured through a hands-on post-assessment to improve learning outcomes in psychomotor skills and spatial thinking when compared to paper instructions. Future work in assessment would also entail measuring advantages associated with reducing instructor load and capturing and standardizing instruction. Additional projects in the machine shop space will focus on promoting student exploration of machining, which can be addressed with a "machining in the dorm room" app where students can carry out different machining tasks without being physically present in the machine shop and can make choices that impact the outcome of their final part.

Lastly, this work is not just for the classroom; industry companies will find these developments useful to pass down "institutional knowledge." Future work would entail expanding the app's usage into industrial contexts for purposes of workforce development and skills archival.

7. Acknowledgements

The authors thank PTC Inc. for Vuforia software and the PTC Education Programs team for their development support. Dan Gilbert supported the piloting of this new module in Mechanical Engineering Tools (2.670). Dr. Glenda Stump gave helpful advice on self-efficacy assessment. Fatima Abbasi carried out hypothesis testing calculations. This work was supported by the d'Arbeloff Fund for Excellence in Education, J-WEL Workforce Learning Innovations Grant, and the MIT Undergraduate Research Opportunity Program.

8. References

1. P.-H. Diao and N.-J. Shih, "Trends and Research Issues of Augmented Reality Studies in Architectural and Civil Engineering Education—A Review of Academic Journal Publications," *Applied Sciences*, vol. 9, no. 9, p. 1840, May 2019, DOI: 10.3390/app9091840.

2. D. H. Uttal and C. A. Cohen, “Spatial thinking and STEM education,” *The Psychology of Learning and Motivation*, pp. 147–181, 2012.
3. Elijah T. Johnson & Karen S. McNeal (2022) “Student perspectives of the spatial thinking components embedded in a topographic map activity using an augmented-reality sandbox”, *Journal of Geoscience Education*, 70:1, 13-24, DOI: 10.1080/10899995.2021.1969862
4. Maggi Savin-Baden, Lesley Gourlay, Cathy Tombs, Nicole Steils, Gemma Tombs & Matt Mawer (2010) Situating pedagogies, positions and practices in immersive virtual worlds, Educational Research, 52:2, 123-133, DOI: 10.1080/00131881.2010.482732
5. J. Martin-Gutierrez, E. Guinters, and D. Perez-Lopez, “Improving strategy of self-learning in engineering: Laboratories with Augmented Reality,” *Procedia - Social and Behavioral Sciences*, vol. 51, pp. 832–839, 2012.
6. OECD (2018), "Embodied learning", in *Teachers as Designers of Learning Environments: The Importance of Innovative Pedagogies*, OECD Publishing, Paris, DOI: 10.1787/9789264085374-en
7. M. C. Johnson-Glenberg, C. Megowan-Romanowicz, D. A. Birchfield, and C. Savio-Ramos, “Effects of embodied learning and digital platform on the retention of physics content: Centripetal force,” *Frontiers in Psychology*, vol. 7, 2016.
8. I. Radu and A. Antle, “Embodied Learning Mechanics and their relationship to usability of handheld augmented reality,” *IEEE Xplore*. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7961561&tag=1. [Accessed: 03-Feb-2022].
9. M. Osborne and S. Mavers, "Integrating Augmented Reality in Training and Industrial Applications," *2019 Eighth International Conference on Educational Innovation through Technology (EITT)*, 2019, pp. 142-146, DOI: 10.1109/EITT.2019.00035.
10. K. Haddad and D. Baglee, “Using Augmented Reality in Manufacturing Firms and its Impacts on Knowledge Transfer,” in *European Conference on Knowledge Management*, Academic Conferences International Limited, 2015, pp. 1037.
11. Pintrich, P.R., Smith, D.A.F., García, T., & McKeachie, W.J. (2015). Motivated Strategies for Learning Questionnaire (MSLQ) Manual. 10.13140/RG.2.1.2547.6968.
12. NIMS Machining Level 1 Preparation Guide Turning, National Institute for Metalworking Skills, Inc., Fairfax, VA, 2003.
13. NIMS Machining Level 1 Preparation Guide Milling, National Institute for Metalworking Skills, Inc., Fairfax, VA, 2003.
14. M. Akçayır and G. Akçayır, "Advantages and challenges associated with augmented reality for education: A systematic review of the literature," *Educational Research Review*, vol. 20, pp. 1-11, 2017.

9. Appendix

Questions to measure affective outcomes (pre- and post- assessment)

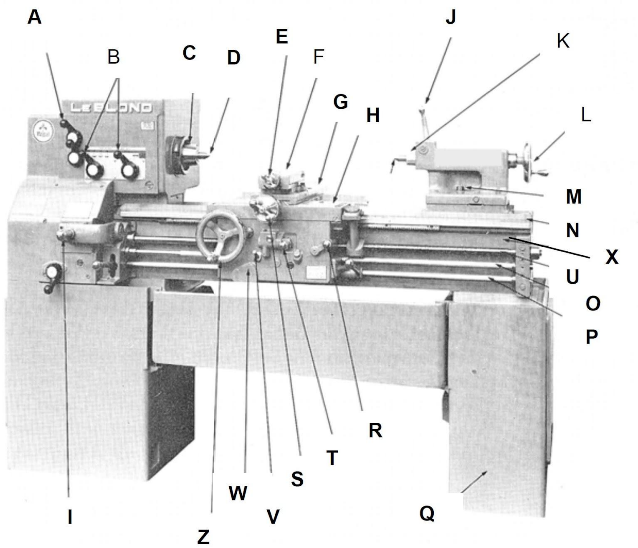
The following questions all work on a 7 point scale defined as follows:

1 – Not at all true of me
2 – Untrue of me
3 – Somewhat untrue of me
4 – Neutral
5 – Somewhat true of me
6 – True of me
7 – Very true of me

1. I'm confident I can use the skills taught in 2.670 for engineering activities.
2. I'm certain I can understand the most difficult material presented in instructions and material for 2.670.
3. I am afraid that mistakes that I make in the shop will cause long-term negative effects to the shop and others.
4. I am confident I can use a milling machine to fabricate a component on my own.
5. I try to schedule my time so that I can engage with machining skills.
6. I'm confident I can use the lathe to fabricate a component on my own.
7. I'm confident I can use the bandsaw to fabricate a component on my own.
8. I am afraid that my own mistakes will cause detriment to my own learning.
9. I believe I will pass 2.670.
10. I'm confident I can understand the basic concepts taught in 2.670.
11. I'm confident I can understand the most complex material presented in 2.670.
12. I will seek out opportunities to engage in machining skills outside of required MechE courses (e.g. electives, independent/club projects).
13. I'm certain I can master the skills being taught in 2.670.
14. I see myself engaging with machining skills for a long time to come.
15. Considering the difficulty of this course, the teacher, and my skills, I think I will do well in 2.670.
16. I am afraid that I will damage machine shop tools and equipment as I am learning.
17. I look forward to the next time I'll be able to engage with machining skills.
18. I am afraid that I will hurt myself or others when using machine shop equipment.
19. I'm confident I can do an excellent job on the assignments and tasks 2.670.
20. I expect to do well in 2.670.
21. I become more interested in machining the more I engage with machining skills.

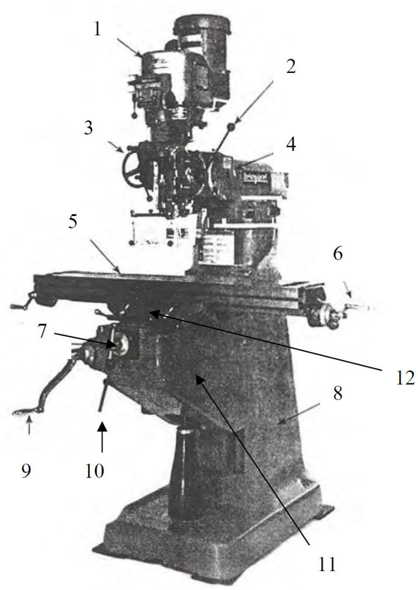
<u>Questions to measure cognitive outcomes (pre- and post- assessment)</u>

Use the following diagram to identify lathe components



22. The carriage of the lathe is identified by the letter:
23. The tailstock of the lathe is identified by the letter:
24. The spindle of the lathe is identified by the letter:
25. Which of the following shapes cannot be held adequately by a 3-jaw universal chuck:
26. The primary advantage of turning between centers is that:

Use the diagram to identify key components of a vertical milling machine



27. Which of the following vertical milling machine components is labeled as 1?
28. Which of the following vertical milling machine components is labeled as 5?

29. Which of the following vertical milling machine components is labeled as 11?
30. Name the tool and process used to precisely enlarge an existing hole:
31. Knurling is:
32. Which of the following is not part of a procedure for knurling?
33. A small tip was left on the end of the part when performing a facing operation on a lathe. The root cause of this problem is:
34. Which of the following are potential safety hazards when operating a lathe?
35. The process plan calls for a 2.5” diameter clearance fit hole. The best process plan is to:
36. Each division found on the thimble of a micrometer is equal to ________ and each division found on the sleeve is equal to ___________.
37. One factor to consider when choosing the appropriate measuring device to measure a specific feature of a part is the:
38. Name the three types of taps found in a tap set:
39. An edge finder has a tip diameter of 0.200 inches. What distance must the table move to align the center of the edge finder to the edge of the workpiece?
40. The most commonly used work holding device on the vertical milling machine is a:
41. Which of the following best describes the procedure for drilling a hole?

<u>Questions to collect student feedback on the activity (post- assessment only)</u>

As you are aware, you received instructional material in an alternate augmented reality (AR) format. Please reflect on your learning experience and answer the following questions.

The following questions all work on a 7 point scale defined as follows:

1 – Not at all true of me
2 – Untrue of me
3 – Somewhat untrue of me
4 – Neutral
5 – Somewhat true of me
6 – True of me
7 – Very true of me

42. I liked learning using the AR experience I received.
43. I learned the necessary material using the AR experience I received.
44. I would prefer to learn machining using the AR experience I was given as opposed to using instructions in a paper format.
45. How did using the AR experience you received facilitate or detract from your learning?

46. Any additional comments?